Precise effective Higgs-gluon interaction in BSM scenarios

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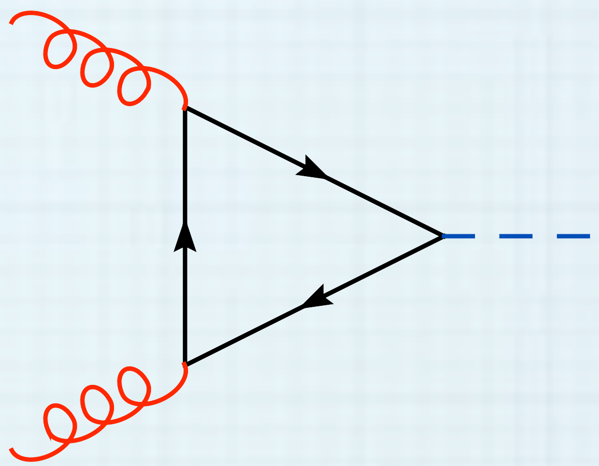
Motivation

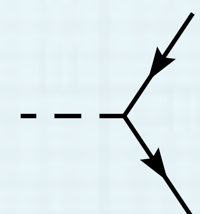
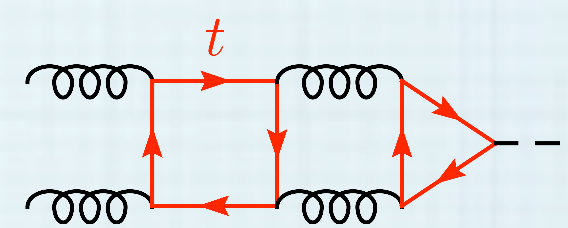
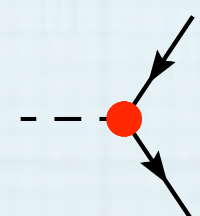
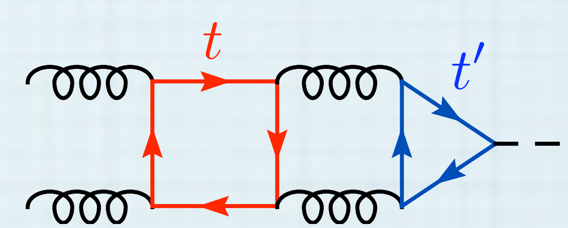
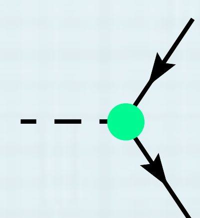


* gluon fusion is the main mechanism for Higgs production at hadron colliders
* it is sensitive to any coloured particle that couples to the Higgs, e.g. the top
* the Higgs sector is untested

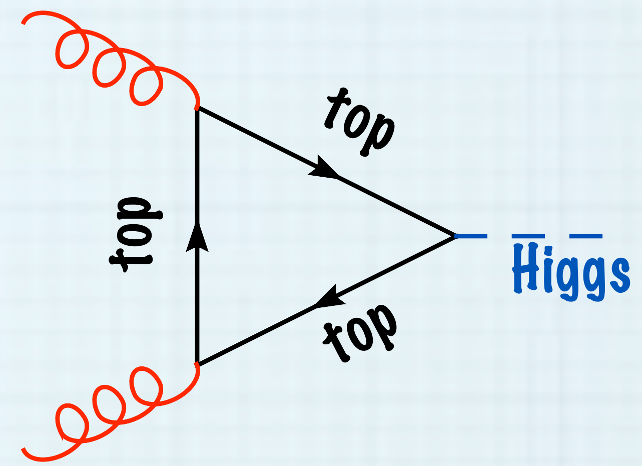
this channel is very sensitive to new physics effects

* the Standard Model Higgs sector is likely to be wrong
* extensions of the SM require new particles which may contribute to gluon fusion

Motivation

particles in different representations of the Lorentz group	particles in different colour representations	different structure of the Higgs coupling	particles of different mass in the loops
quarks	singlets, triplets, octets	 $\sim \bar{\psi}\psi$	
scalars	fundamental, adjoint	 $\sim \bar{\psi}\gamma_5\psi$	
Majorana fermions	⋮	 $\neq \frac{m}{v}\bar{\psi}\psi$	⋮
⋮		⋮	

Gluon fusion in the SM



* it is known very precisely...
* ... but it required tough calculations

$$\sigma^{(SM)}_{NNLO} = \sigma^{(SM)}_{LO}\,(1 + \underbrace{0.7}_{\text{NLO}} + \underbrace{0.3}_{\text{NNLO}})$$

Harlander, Kilgore;
Anastasiou, Melnikov;
Ravindran, Smith, van Neerven

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{\exp} \sim \pm 10\% \qquad , \qquad \left(\frac{\Delta\sigma}{\sigma}\right)^{NNLO}_{SM} \sim \pm 10\%$$

* ... and integrating out the top quark (HQET)
  (Chetyrkin, Kniehl, Steinhauser)

Gluon fusion in BSM

* Only very recent NNLO calculations in some BSM scenarios
  - ➡ scalar octects (Boughezal, Petriello)
  - ➡ fourth generation (Anastasoiu, Boughezal, EF)
* Why?

  The low-energy theory is usually the same as in SM HQET, but the matching calculation at NNLO is much more complicated:
  * number of diagrams
  * renormalization
  * dependence on multiple mass scales

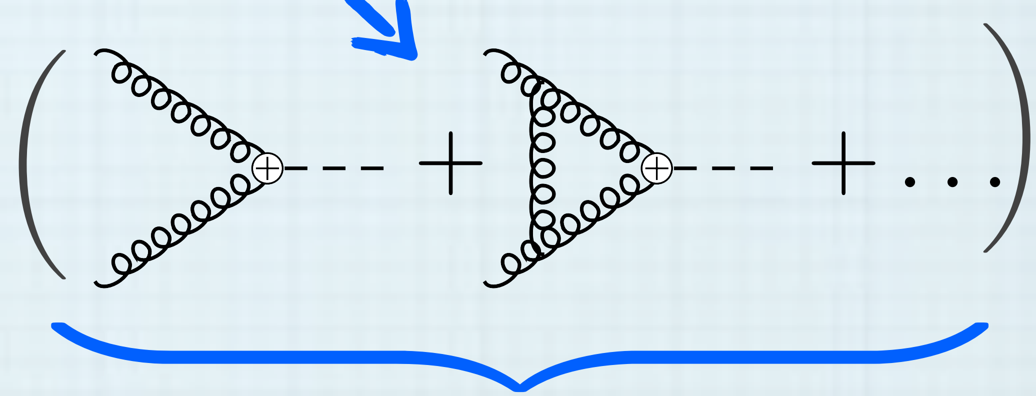
Separating new physics

* experiments (LEP, Tevatron, ..) indicate that new particles must be heavy, while the Higgs is light

* this allows for an effective-theory approach:

$$\mathcal{L}_{eff} = -\frac{\alpha_s}{4v} C \, H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\underbrace{\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \dots \right)}_{\text{depends on the specific model}}$$



QCD only!

→ factorization of QCD and NP effects

Technical challenges

* Large number of Feynman diagrams

  $\sim$ 500 in the SM, $\sim$ 6000 in composite Higgs, ...

* Reduce a large number ($\sim 10^5$) of integrals to master integrals

  ➡ we wrote our own routines in
    - ✦ QGRAF (Nogueira)
    - ✦ Mathematica
    - ✦ FORM (Vermaseren)
    - ✦ AIR (Anastasiou, Lazopoulos)

  ➡ same methods for SM and BSM Wilson coefficients

Technical challenges

* Evaluate the master integrals

➡ much more difficult than in the SM (many mass scales)

➡ in many cases, impossible with traditional analytic methods -> sector decomposition

Hepp; Denner, Roth; Binoth, Heinrich; Anastasiou, Melnikov, Petriello; Anastasiou, Beerli, Daleo; Lazopoulos, Melnikov, Petriello

Composite Higgs models

Georgi, Kaplan

* class of models that address the hierarchy problem
* idea:
  - there is a new, strongly interacting sector responsible for EWSB
  - the Higgs boson is a bound state of this new sector
    ⇨ its mass is not sensitive to radiative corrections above the compositeness scale
  - the new sector possesses a spontaneously broken global symmetry

Composite Higgs models

Georgi, Kaplan

- the Higgs boson is the pseudo Goldstone boson associated to this symmetry breaking
  ⇨ its mass is naturally light
- SM particles get their masses through mixing with composite fermions
  ⇨ heavy SM quarks (top) are largely "composite", so they couple more to the Higgs boson
  ⇨ couplings to the Higgs boson are reduced with respect to the SM
  ⇨ we have new heavy fermions!

... Higgs production?

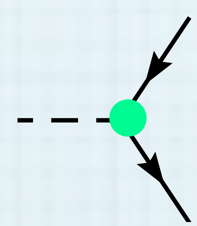
how does this affect the Higgs searches?

... Higgs production?

* at LO, expect a suppression in the Higgs boson production via gluon fusion (Falkowski)
* the suppression factor depends on the details of the model (group structure, embedding of the composite fermions into the symmetry group, scale of symmetry breaking)
* for the model that is more favoured by current experimental bounds,
$$\frac{\sigma_{CH}^{LO}}{\sigma_{SM}^{LO}} \sim 35\%$$
* (how) does this result change at higher orders?

Calculation

* differences with respect to the SM:
    * the coupling of the quarks to the Higgs boson is not proportional to the mass



$$\cancel{\frac{m_1}{v}} \longrightarrow Y_1$$

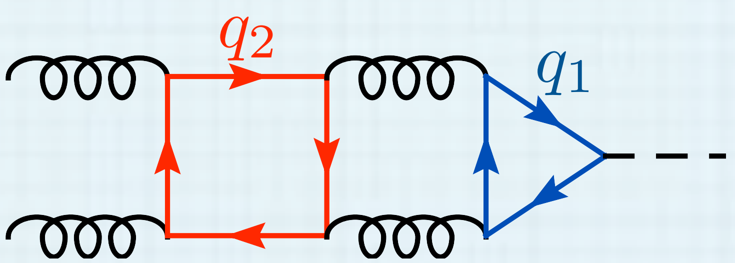
renormalization?

Y_1 renormalizes as the mass, $Y_1 = Z_m Y_1^R$

(Chetyrkin, Kuhn, Kwiatkowski)

Calculation

* differences with respect to the SM:
  - at NNLO, we have diagrams containing two different heavy quarks

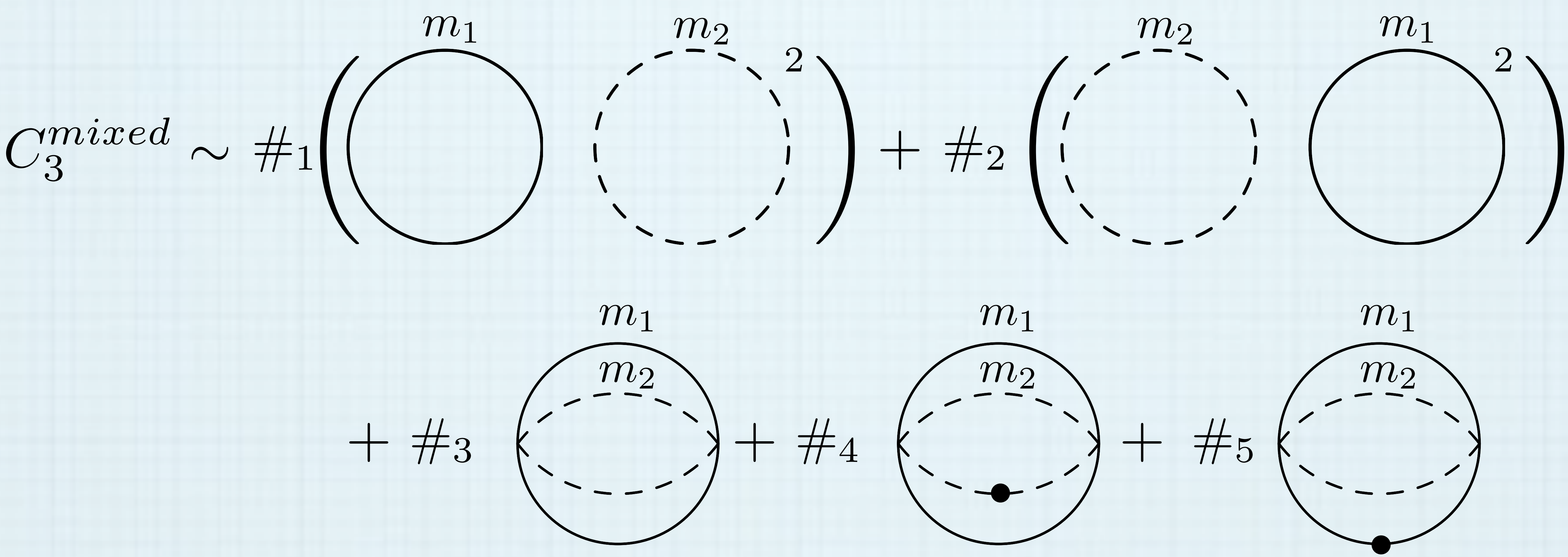


⇨ master integrals now contain up to two, different, massive propagators

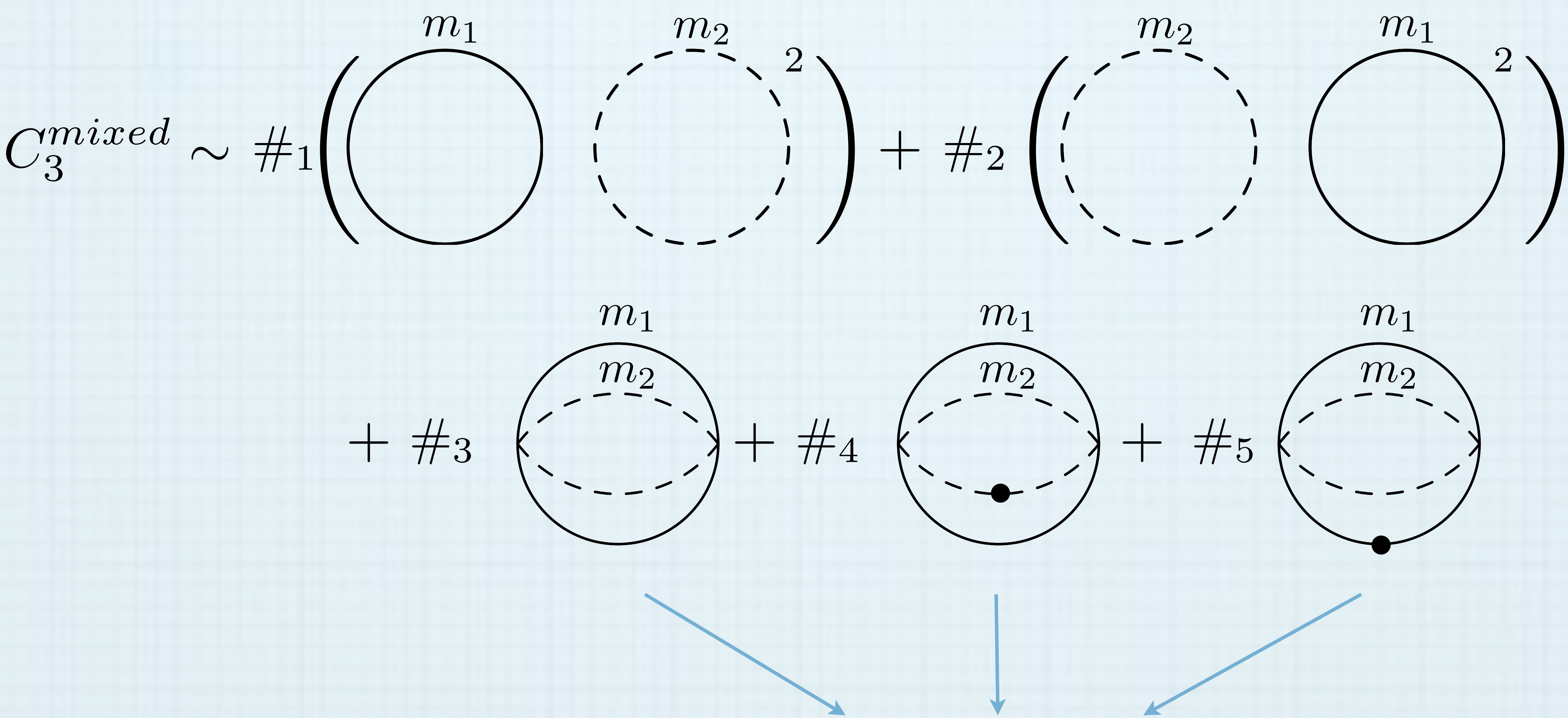
⇨ hundreds of such diagrams

⇨ contributions also from heavy quarks that do not couple to the Higgs boson

Calculation

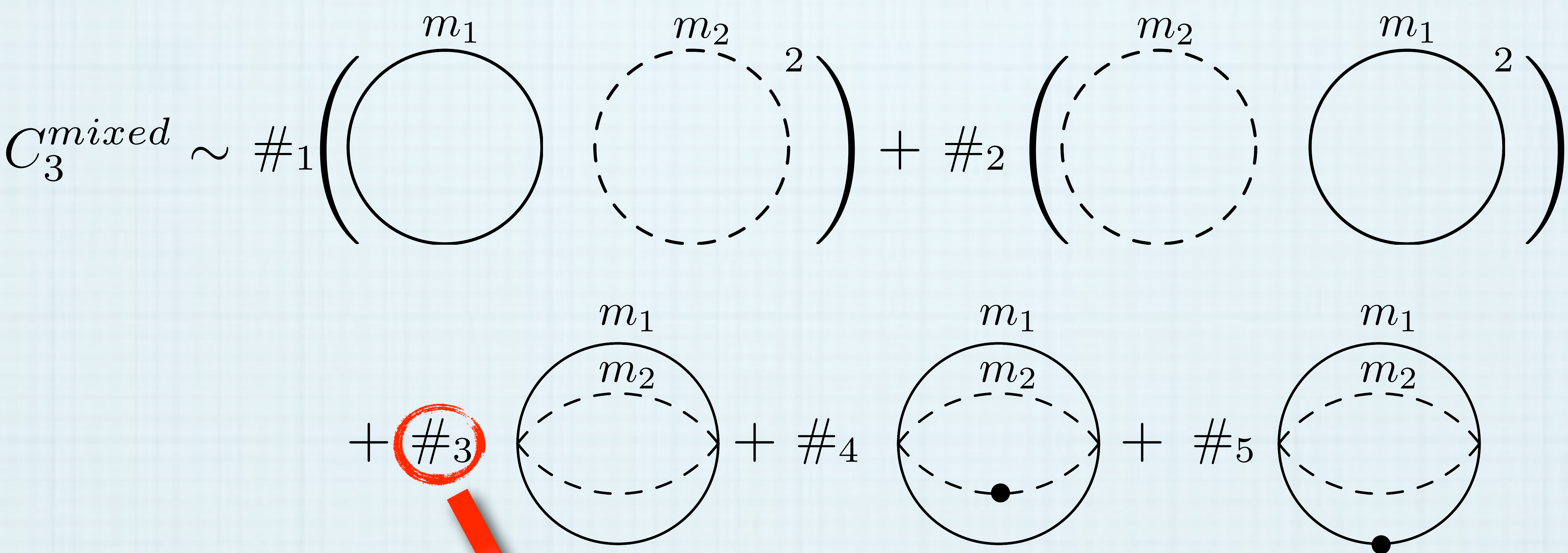


Calculation



Bekavac, Grozin, Seidel, Smirnov

Calculation

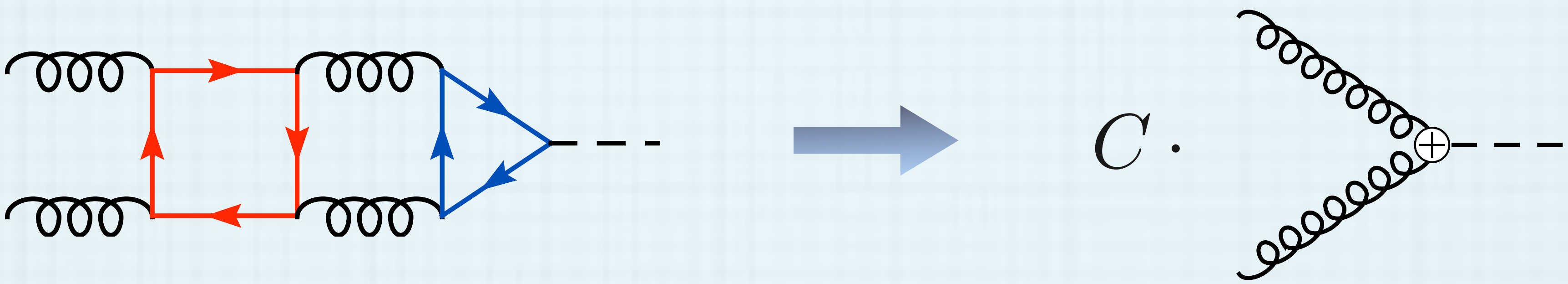


$$\frac{\alpha_s^3}{2m_1^4 m_2^6}\frac{Y_1}{m_1}\left[\frac{\left(19m_1^6+5m_1^4m_2^2-5m_1^2m_2^4-19m_2^6\right)}{\epsilon} - \frac{1713m_1^8+476m_1^6m_2^2-1834m_1^4m_2^4-964m_1^2m_2^6-1023m_2^8}{36(m_1^2-m_2^2)}\right]$$

Decoupling

- We want to construct an effective theory that only contains light particles

- So far



➡ the heavy quarks also give loop contributions to self-energies and vertices of light fields

➡ absorb these contributions into decoupling constants
(Chetyrkin, Kniehl, Steinhauser)

Result

* the three loops Wilson coefficient is..

$$
\begin{aligned}
&\left(\frac{\alpha_s'(\mu)}{\pi}\right)^2 \Bigg\{ L_0 \left[\frac{1877}{192} - \frac{77}{576} n_h + \sum_{i=1}^{n_h} \left(\frac{113}{96} \log\left(\frac{m_i}{\mu}\right) + \frac{3}{8} \log^2\left(\frac{m_i}{\mu}\right) \right) \right] \\
&\quad - L_1 \left[\frac{19}{8} + \frac{113}{96} n_h + \frac{3}{4} \sum_{i=1}^{n_h} \log\left(\frac{m_i}{\mu}\right) \right] + \frac{3}{8} n_h L_2 - n_l \left(\frac{67}{96} L_0 + \frac{2}{3} L_1 \right) \\
&\quad + \sum_{\substack{1 \le i < n_h \\ i < j \le n_h}} \Bigg[(y_i - y_j) \left(\frac{57}{128} \left(\frac{m_i^2}{m_j^2} - \frac{m_j^2}{m_i^2} \right) + \left(\frac{57}{128} \frac{m_i^2}{m_j^2} + \frac{57}{128} \frac{m_j^2}{m_i^2} + \frac{43}{32} \right) \log\left(\frac{m_i}{m_j}\right) \right. \\
&\qquad \left. + \frac{57}{256} \frac{m_i^6 + m_j^6}{m_i^2 m_j^2 \left(m_i^2 - m_j^2\right)} \log^2\left(\frac{m_i}{m_j}\right) \right) - \log^2\left(\frac{m_i}{m_j}\right) \left(\frac{73}{256} (y_i + y_j) + \frac{23}{128} \frac{y_i m_i^2 - y_j m_j^2}{m_i^2 - m_j^2} \right. \\
&\qquad \left. + 3\left(m_i^2 - m_j^2\right) \frac{19 m_i^4 + 24 m_i^2 m_j^2 + 19 m_j^4}{512 m_i^3 m_j^3} \left(y_j \log\left(\frac{m_j - m_i}{m_j + m_i}\right) - y_i \log\left(\frac{m_i - m_j}{m_i + m_j}\right) \right) \right) \\
&\qquad - 3 \frac{19 m_i^6 + 5 m_i^4 m_j^2 - 5 m_i^2 m_j^4 - 19 m_j^6}{1024 m_i^3 m_j^3} \left(8 y_i \mathrm{Li}_3\left(\frac{m_j}{m_i}\right) - 8 y_j \mathrm{Li}_3\left(\frac{m_i}{m_j}\right) - y_i \mathrm{Li}_3\left(\frac{m_j^2}{m_i^2}\right) \right. \\
&\qquad \left. + y_j \mathrm{Li}_3\left(\frac{m_i^2}{m_j^2}\right) - 2 \log\left(\frac{m_i}{m_j}\right) \left(y_i \mathrm{Li}_2\left(\frac{m_j^2}{m_i^2}\right) + y_j \mathrm{Li}_2\left(\frac{m_i^2}{m_j^2}\right) - 4 y_i \mathrm{Li}_2\left(\frac{m_j}{m_i}\right) - 4 y_j \mathrm{Li}_2\left(\frac{m_i}{m_j}\right) \right) \right) \Bigg] \Bigg\}
\end{aligned}
$$

$$
y_i = \frac{Y_i}{m_i} \;,\; L_0 = \sum_i y_i \;,\; L_1 = \sum_i \left(y_i \log(m_i)\right) \;,\; L_2 = \sum_i \left(y_i \log^2(m_i)\right) \;.
$$

Higgs production cross-section in composite Higgs models

* we consider a composite Higgs model with an SO(5)/SO(4) symmetry breaking pattern

* we include composite, vector-like fermions that transform under the fundamental representation of SO(5)
  ⇨ multiplets that contain

  three charge 2/3 quarks
  one charge -1/3 quark
  one charge 5/3 quark

  mix with the SM top bottom

  does not couple to the Higgs boson

Higgs production cross-section

* calculation of the cross-section:
  - ➡ compute the NLO and NNLO K-factors in the effective theory
  - ➡ multiply them by the exact LO cross-section

$$\sigma^{NNLO} \simeq \left(\frac{\sigma^{NNLO}}{\sigma^{LO}}\right)_{effective} \cdot \sigma^{LO}_{exact}$$

Higgs production cross-section

	$\frac{\sigma_{CH}^{LO}}{\sigma_{SM}^{LO}}$	$\frac{\sigma_{CH}^{NLO}}{\sigma_{SM}^{NLO}}$	$\frac{\sigma_{CH}^{NNLO}}{\sigma_{SM}^{NNLO}}$
one multiplet	32 - 34%	32 - 35%	30 - 35%
two multiplets	33 - 34%	33 - 35%	30 - 36%

20%?

110%?

preliminary

Higgs production cross-section

	$\frac{\sigma^{NLO} - \sigma^{LO}}{\sigma^{LO}}$	$\frac{\sigma^{NNLO} - \sigma^{LO}}{\sigma^{LO}}$
SM	76%	106%
one multiplet	78 - 79%	95 - 110%
two multiplets	79 - 80%	100 - 120%

Higgs production cross-section

- the estimate of a 35% suppression of the Higgs boson production cross-section is, in general, a good approximation
- however, in some regions of the parameter space we can get large deviations from this estimate
- NNLO K - factors are typically 90-110% of the SM K-factor
- theory uncertainties are similar to the SM
  -> only at NNLO, the theoretical uncertainty matches the experimental uncertainty

Conclusions

* the Higgs boson is likely to come with some new physics
* many viable BSM theories exist, and many need to introduce new particles
* new particles can significantly affect the gluon-fusion cross section
* effective theory disentangles new physics from QCD
* we have automatised the matching procedure for BSM models through NNLO
* ready for high-precision predictions for Higgs boson cross-section in extensions of the SM
* example: composite Higgs model